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β Pictoris: Evidence of light variations. *

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Abstract. We have analyzed β Pictoris photometric measurements obtained from La Silla by the Geneva Observatory from 1975 to 1992. These data show evidence of variations in the brightness of the star, with no color dependency. Here, we demonstrate that the light variations are present on long as well as on short time scales.

On a long time scale, we show that the apparent magnitude of β Pictoris decreased by $0^m.011 \pm 0^m.004$ from 1979 to 1982. Moreover, when we consider all the measurements, the chance that there is no variation at all can be estimated to be less than 10^{-4} . On short time scales there is a peculiar feature observed during about 30 days; the variations may be as high as $0^m.04$ magnitude. A maximum entropy reconstruction of the photometric data is tentatively proposed and some physical interpretations are presented.

Key words: stars: β Pic – circumstellar matter – planetary systems

1. Introduction

Following the Geneva Observatory photometry measurements obtained from La Silla (Rufener 1989), we were able to analyze the β Pictoris (HR 2020, HD 39060) photometric variations. The data presented here were obtained from Nov 18, 1975 to Feb 27, 1992 (Julian Day 2442734 to 2448679)¹.

In 1975, β Pictoris was used by the Geneva Observatory as a reference star. But, although the "Vega-like" phenomenon was not yet known (Aumann et al. 1984),

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it was noted that β Pictoris showed some variations, and it was eliminated from the list of reference stars in 1982. Unfortunately, the consequence was that this star was not observed any more until 1988, when we suggested to start again its photometric survey. Indeed, β Pictoris was noted as a very peculiar star in 1984 (Smith & Terrile 1984). In ten years a large number of observations of the disk were performed in optical imagery with coronographs (Smith & Terrile 1987, Paresce & Burrows 1987, Golimowsky et al. 1993) or anti-blooming CCD (Lecavelier des Etangs et al. 1993), in infrared photometry (Backman et al. 1992) and imagery (Lagage & Pantin 1994). Meanwhile spectroscopic studies carried out on a large range of wavelengths have led to analysis of the gaseous counterpart of the disk: in the UV with IUE (Kondo & Bruhweiler 1985, Lagrange-Henri et al. 1989, Deleuil et al. 1993) and HST (Boggess et al. 1991, Vidal-Madjar et al. 1994), in optical (Hobbs et al. 1985, Vidal-Madjar et al. 1986, Ferlet et al. 1993, Crawford et al. 1994) and infrared (Knacke et al. 1993, Aitken et al. 1993). The circumstellar spectral lines show strong evidence of variations, which are presently interpreted as comets falling onto the star (Beust et al. 1991, Beust & Tagger 1993). The last HST observations (Vidal-Madjar et al. 1994) strongly confirm our model and its predictions. The presence of numerous large bodies in the β Pictoris circumstellar disk is a more and more reasonable hypothesis.

However, analysis of photometric variation is a new approach which has never been tried for β Pictoris. As already mentioned, we proposed in 1989 to return β Pictoris to the list of stars observed by the Geneva Observatory. Despite the lack of photometric measurements from 1983 to 1988, the data collected until now cover a very long time base that amounts to almost twenty years. It is now possible to extract some important and new information, and especially statistical information derived from data taken over a large time scale .

^{*} Based on observations obtained at the European Southern Observatory (ESO), La Silla (Chile)

data-file available electronically at IAP via anonymous ftp on corton.iap.fr /pub/from_users/lecaveli/

The data are presented in Sect. 2. In Sect. 3 and 4, we shall show the analysis of the variations in terms of long and short time scales. Some physical interpretations are presented in Sect. 5

2. Presentation of the data

Throughout the paper, we shall subtract a constant (2440000) from the Julian Day, for simplicity, considering the four last significant digits; for example Julian Day 2444918 will be designated as JD 4918. The measurements are composed of one V magnitude and six color index measurements corrected for atmospheric extinction: V, U-B, V-B, B₁-B, B₂-B, V₁-B, G-B (Rufener & Nicolet 1988). Thus, the same tests can be performed on all these seven quantities. But, as we shall see, except in the section 3.3, the color determinations do not show variations.

The magnitude measurements are associated with a quality factor from 0 to 4 in which 4 is the best quality measurement. If we consider all the data irrespective of the quality factor, the results are the same as those presented here, but the probabilities are not so well distributed (see below), so the uncertainties cannot be estimated easily. Among the 238 measurements of β Pictoris, we considered only those 155 measurements that have a quality greater than or equal to 3.

All the statistical tests we performed on these data were also performed on 8 other stars to check the reality of the variations observed and to confirm that the probabilities are well distributed. These stars are the following with the number of measurements with quality greater than or equal to 3 in brackets: HR 10 (64), HR 33 (157), HR 1801 (82), HR 2154 (198), HR 2174 (41), HR 6389 (67), HR 6519 (6), HR 7316 (216).

3. Long term variations

3.1. Estimate of the parameters and the significance levels

In this section, we consider each V measurements (V_i) as a function of the time (t_i) . In order to estimate the variations of the magnitude measurements and the significance of these variations, we used least square methods, and tried to fit the data with two models, that is first and second degree polynomials. In each case, we compute the variance of the parameter estimates, so we are able to conclude if the variations are significant or not. In other words, we estimate the probability that the result is only an artifact of statistical random variations, which would mean that the magnitude data do not reveal real variations, and represent only randomly distributed deviations around the real magnitude of the star.

The two models are: $V_1 = a_1 + b_1 \cdot t$ and $V_2 = a_2 + b_2 \cdot t + c_2 \cdot t^2$. In the first model, $s_{b_1}^2$ is an estimate of the variance of b_1 : $s_{b_1}^2 = Q_1/(N-2)\sum_i^N (t_i - \overline{t})^2$ with $Q_1 = \sum_i^N (V_i - V_1(t_i))^2$.

The probability that the estimator $|\hat{b}_1|$ is as high as the calculated estimate $|b_1(V_i, t_i)|$, under the hypothesis that b_1 is zero, gives a good estimation of the probability that there is no signal. We use the fact that \hat{b}_1/s_{b_1} follows a Student law with N-2 degrees of freedom, if there are N measurements.

In order to check if the addition of the t^2 term in the second model improves the goodness of fit of the first model, we evaluate $F = (Q_1 - Q_2)(N-3)/Q_2$ where $Q_2 = \sum_i^N (V_i - V_2(t_i))^2$. If the t^2 term does not improve the fit, then $Q_1 = Q_2$ and F = 0. On the other hand, if F is very high, thus $Q_1 \gg Q_2$, the data will strongly depend on the t^2 term. \hat{F} follows a Fisher-Snedecor law with 1 and (N-3) degrees of freedom. The probability that \hat{F} is as high as the calculated one is an estimate of the probability that the magnitude of β Pictoris does not depend on the t^2 term.

3.2. Data until 1982

From 1975 to 1982 we have a nearly continuous set of data. But, in the time span between Nov 18, 1975 to Feb 16, 1976, we have only five points which are obviously at higher magnitude (Fig. 1). These data are very early measurements and are followed by a lack of measurements during four years. In order to avoid any bias in the data before JD 3000, we decided to focus on the more reliable data from 1979 to 1982

Indeed from JD 3925 to JD 5017, we have 50 measurements of β Pictoris. During this period of time, none of the eight other stars analyzed shows significant variations in any passbands. If we take the 50 first measurements of these eight other stars after the JD 3900, only for one star (HD 41 692) they show a faint signal $(b_1/s_{b_1}=2.0)$ with a chance of 6 % that b_1 is zero. But, since we consider eight stars, this result can take place 39 times in a series of 100 experiments with eight stars with no variation at all. Thus, we can conclude that as far as the eight other stars are concerned there are no significant variations.

However, this is not the case for β Pictoris. It shows a linear variation in the V magnitude measurements with a slope $b_1 = -1.1 \cdot 10^{-5} \pm 0.4 \cdot 10^{-5}$ mag per day during about one thousand days. The fitted curves are plotted in Fig 1. With $b_1/s_{b_1} = 2.7$, the chance that this result is only due to randomly distributed variations is 0.8 %. There is no significant variation in the color data, this slope occurred with almost the same amplitude in all wavelengths from 3464 Å to 5807 Å (U to G filters). The addition of the t^2 term does not improve the fit, since F = 0.01; the probability that the measurements depend on the t^2 term is less than 9%.

We shall now mention that the five magnitude measurements before JD 3000 are located exactly over the extrapolation of the variations which we have described in this section and will further be discussed in section 3.4.



Fig. 1. Plot of the magnitudes (crosses) as a function of Julian day with quality factor greater than or equal to 3, and curves fit to the data: full line from JD 3925 to JD 8260. Dot-dash line from JD 2734 to JD 8260. Dashed line from JD 3925 to JD 5017. Dotted line from JD 2734 to JD5017. The data before JD 3000 are represented by asterisk. With no threshold in quality factor, the fits to the data would be almost identical

We have plotted the fits with and without these early measurements. Almost identical fits are found.

3.3. From 1989 to 1992.

The fit of this set of data by the first or second degree polynomials gives that the probability that the slope and the second degree coefficient in the parabola is zero, is $3 \cdot 10^{-3}$ in the first case, and $6 \cdot 10^{-6}$ in the second one. We can conclude that we are dealing with strongly significant signal. However as could be seen from Fig. 1, this result is strongly correlated with the first group of data from JD 7767 to 7795 (September 1989) whose magnitudes are smaller than the following ones by about $0^m:01$. In order to check if this effect is really due to the first group of data, we isolated the data from JD 7873 to the end. In the case where the fit were made on the whole set of data from JD 7873 to JD 8679, we found almost no variation: the chance that the slope is zero can then be evaluated to be 18%.

Moreover, we emphasize that the feature of September 1989 is also present in the V-B, V_1 -B and G-B data, with a drop of the V-B color of about 0?005, while the U-B, B_1 -B and B_2 -B colors do not show significant variations. If we consider the first group of data relative to the ones after JD 7873 (December 1989), the enhancement of the brightness in the short wavelength seems to be only half that at longer wavelengths. This result is strongly confirmed by observations of the reference stars, which during the same period showed no significant variation.

3.4. Global analysis of the data.

Although there is a large discontinuity in the collected data set, we analyzed them in the same way from a global point of view. With the linear model, we find a slope with a probability of 10^{-4} that it is zero. Furthermore, in the second model, the probability that the second degree polynomial coefficient is zero, is $7 \cdot 10^{-4}$. This result is presented in Fig. 1 where we have plotted this parabola with and without the data before 1976. We are aware that this variation should not be polynomial, but, we do not have enough information to conclude on the shape of the curve; moreover, the relation between the first part of the measurements and the second part is not completely obvious. However, this allows to definitely show that, in the long term, there is clearly a variation of the magnitude of β Pictoris.

We can check in a very simple manner that the probabilities are well determined. If we look at the probability that there is a variation (for example that the slope is different from zero) in a reference star supposed to be constant, this probability must be uniformly distributed between 0. and 1. For a group of reference stars, we can therefore sort their probabilities into ascending order and plot them in this order; then, they must follow a straight line from 0. to 1.

The variations were investigated with both models. The result is illustrated on Fig 2, where we have plotted the probabilities that b_1 and c_2 are zero in the analysis of the eight reference stars. We see that they effectively follow the straight line; they are uniformly distributed between 0. and 1., proving that the magnitudes are purely randomly distributed. Systematic errors must exist in the data with no threshold on the quality factor since, as shown in Fig. 2, the probabilities are not as well behaved.

3.5. IUE Fine Error Sensor observations.

The Fine Error Sensor (FES) is used by the IUE satellite for target acquisition and offset guiding (see for example Imhoff, 1989). The FES counts value can be used to estimate an equivalent V magnitude, using an appropriate calibration procedure taking into account the stellar color (B-V), the focus step, time correction and changes of the zero point (Perez & Loomis 1991).

From 1984 until the present, more than two hundred FES counts values have been recorded for β Pictoris. We thus decided to check if this large set of data can be used to compensate for the lack of measurements. However, since February 1991, the field of view of the FES is contaminated by a background scattered light (Monier, 1992). Moreover, from November 1992, this scattered light has strongly increased with time (Rodriguez Pascual, 1993; Garcia-Lario et al., 1993). We have thus excluded observations recorded after this date.

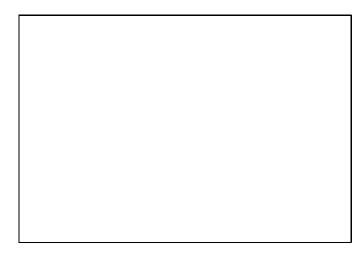


Fig. 2. Distribution of the probabilities that b_1 (empty square) and c_2 (filled square) are zero among the references stars with a threshold in the quality factor. It is obvious that these probabilities are uniformly distributed between 0 and 1. The triangles represent the same thing with no threshold in the quality factor. In this case, the probabilities are not well determined. The two first x are those of β Pictoris for which b_1 and c_2 are clearly different from zero

In this analysis, we used HD 34 816 (λLep) as an IUE standard star (see e.g. Huber & Perez, 1991). For this standard star, we get 91 measurements obtained from 1979 to 1991. The FES derived magnitudes of this star as a function of time shows absolutely no variation at all, and yields a mean value of V(FES)=+4.21 with a standard deviation of 0°:05 which shows the poor accuracy of these data compared with the Geneva Observatory photometry.

For β Pictoris after the different FES corrections, we obtain a set of 201 measurements from 1984 to 1992. Only 9 measurements has been left out, they are obviously wild points out of the distribution. The variance of the remaining 192 measurements of β Pictoris (0.0025 mag²) is too large to confirm the features observed in the Geneva Observatory measurements. We simply note that the points after JD 8500 (those of 1992) seem to indicate a slow drop in the magnitude of about 0 m :02; but we are know that since 1991, the FES data are more and more contaminated by scattered light and the reference star was not observed during this period. These data only show that a long term variation of more than 0 m :05 is not present from 1984 to 1988. Analysis of better quality measurements is the only way to extract information for this period.

3.6. Conclusion

In the long term, we have found that there are two noteworthy variations. The first one during one thousand days (from JD 3927 to 5017), when there was an enhancement of the β Pictoris brightness of $0^m.011 \pm 0^m.004$ from 1979 to 1982, with no associated variations in color. These vari-

ations have a significance level of more than 99.2 %. The second variation happened around JD 7780 (September 1989). During this period the V magnitude of β Pictoris was 0°:01 below the measurements after JD 7767 (December 1989). At shorter wavelengths (U band), the enhancement was only of 0°:005. Finally, the global analysis of the data enable us to definitely show that there is clearly a variation of β Pictoris brightness on a long time scale.

4. Short term variations

4.1. Estimation of the variance of the data

For short term variations, the analysis method used in section 3 could not be applied, because here the variations are present only over a small part of the data. In order to clear up the possibility of variations on short time scales, we propose to use a statistical method based on the variance estimate of different data samples.

In order to compare the variance of the data of different stars, we used the Snedecor law, which describes the connection between two estimates of the variance. Among the eight stars we analyzed, we found that there are three different groups of similar variances. Four stars belong to the first one with $\sigma^2=1.8\cdot 10^{-5}~{\rm mag}^2$: HD 35 580, HD 41 692, HD 155 450, and HD 180 885. The second group include two stars with $\sigma^2=3.2\cdot 10^{-5}~{\rm mag}^2$. Finally, we have β Pictoris with $\sigma^2=6.8\cdot 10^{-5},$ and HD 256, from JD 7889 to 7903 (29 measurements) where the variance is $\sigma^2=1.3\cdot 10^{-4},$ and from JD 8161 to 8180 (35 measurements) where the variance is $\sigma^2=1.2\cdot 10^{-5}$. It seems that during the first period of observation, there was a significant short time variation. This fact will be discussed in the next section.

As regards β Pictoris, the high value of the variance is due to the data from Oct 14, 1981 to Feb 17, 1982 (JD 4891 - 5017). In order to eliminate the effect of long term variations as observed in section 3.2, we grouped together the measurements taken in a given year, and if we do not take into account the data of 1981-1982, then we can estimate that the inter-class variance is $\sigma^2 = 3.0 \cdot 10^{-5}$. This variance is probably enhanced by the presence of the feature described in sect 3.3, and must thus be regarded as an upper limit. However we shall use this value in the following section since an upper limit is what we need.

4.2. What was going on around β Pictoris on Nov 10, 1981?

Following the results of the previous section, we now suppose that the variance of the data is $\sigma_0^2 = 3.0 \cdot 10^{-5}$, which is an upper limit. For each year of observation of each star, we have computed $s^2 = \sum (V_i - \bar{V})^2 / \nu$, where $\nu = n-1$ if n is the number of measurements. The presence of a signal, with a confidence level of 99%, is established when $s^2 > \sigma_0^2 \chi_{\nu}^2 (0.99) / \nu$.

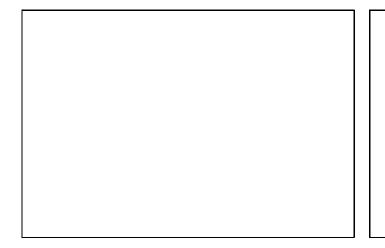


Fig. 3. Data of HR 256 (crosses) and their maximum entropy reconstructions averaged per day (full line). This gives a lower limit of the amplitude of the variation, assuming that the reconstruction is compatible with the observations at a confidence level of 99%

Among all the periods of observation of all the stars (with 45 groups of data), only two groups effectively show a signal with a confidence level of 99%: HD 256 from JD 7889 to JD 7903 and β Pictoris from JD 4891 to JD 5017. These data are plotted in Fig 3 and Fig 4. The chance that the variance is $3.0 \cdot 10^{-5}$ could be estimated to be $1.8 \cdot 10^{-14}$ in the first case, and $2.3 \cdot 10^{-10}$ in the second one. For β Pictoris, if we do not take into account the most strange data of JD 4918, then the chance is still $1.5 \cdot 10^{-5}$.

In conclusion, photometric measurements support the presence of a short time scale variation, with a good level of confidence. We have thus tried to evaluate the strength of these variations. The estimate of a lower limit of the amplitude of the variation has been carried out using a maximum entropy reconstruction of the data, the constraint being that the reconstruction is compatible with the observations at a confidence level of 99%: (Skilling & Bryan 1984). If f_i is the reconstruction of the data V_i and A the mean magnitude, then we maximize:

$$S(f) = -\sum_{i=1}^{N} f_{j}[\log(f_{j}/A) - 1]$$

under the constraint that $\sum (f_j - V_j)^2/\sigma_0^2 \leq \chi_N^2(0.99)$. The results for HD 256 and β Pictoris are illustrated on figures 3 and 4. For β Pictoris, the reconstruction gives a lower limit of 0.01 magnitude of variation. It is extremely interesting to see that the variations of β Pictoris are regular (except for JD 4918), symmetrical and centered on this peculiar date. We lay stress the fact that, during this particular night, the atmospheric conditions were very good, and for all the stars observed during this night the measurements were totally normal.

Fig. 4. The same as Fig 5. with the data of β Pictoris The most strange data of Nov 10, 1981 (JD 4918) are represented by circled crosses. The dashed line represents the mean magnitude of β Pictoris. This reconstruction gives a lower limit of 0.01 magnitude of variation with a 99% confidence level

5. Discussion

We now have to deal with the variations with different time scales, for which we must explain the durations as well as the amplitudes. We propose some explanations, but we are aware that they are only tentative in this new field of study of β Pictoris.

Concerning HD 256 (HR 10), the observed variations ($\Delta V \sim 0$ °.02) are not totally surprising since this star shows strong spectroscopic variations which present some similarity with those of β Pictoris (Lagrange-Henri et al. 1990a, 1990b). However no circumstellar disk was detected (G. Perrin, private communication). The interpretation of this photometric phenomenon would be too much speculative, since photometric variability may be also seen in shell stars.

For β Pictoris, the situation is much better since a number of studies have been made during the last 10 years. We are aware that we cannot completely exclude the presence of variations of the intrinsic stellar brightness. However, we think that these variations are also compatible with disk inhomogeneities for which optical observations give some indications. Indeed, basing their conclusions on a midsize grain model, Artymowicz et al. (1989) concluded that the optical depth calculated from β Pictoris outwards to infinity in the midplane of the disk is $0^m.03 \le \tau_{\parallel} \le 0^m.07$. This optical depth would be larger in a model with large grains. A tilt of the disk by less than 5° makes that the extinction of the β Pictoris light towards the Earth decreases to only 0.95 of its maximum value. Therefore, an inhomogeneity of 10% to 20% in the disk azimuthal distribution of dust can easily produce the variations we have observed.

Moreover, from a theoretical point of view, it has been demonstrated (Scholl et al. 1993, Sicardy et al. 1993, Roques et al. 1994) that the presence of a planet in the β Pictoris disk can produce inhomogeneities, such as arcs or an accumulation of matter following the planet trajectory. These structures can explain the variations on a long time scale. With a period of more than 2 000 days, the hypothetic planet responsible for such variations must be at more than 6 AU from the star.

For the short time scale variations, we know that close encounters of particles with a planet lead to accretion or ejection of these particles into eccentric orbits (Roques et al. 1994). Thus, the sphere of influence of the planet must be relatively clear of dust. We propose that the enhancement of brightness of β Pictoris around day 4918 could be due to the passage of this cleared out zone in front of β Pictoris. To cover a distance equal to its Hill radius, the planet needs a time t_H :

$$t_H = 32 \left(\frac{M_p}{M_J}\right)^{1/3} \left(\frac{D}{5\text{AU}}\right)^{3/2} \text{ days}$$

Here M_p is the mass of the planet, M_J is the mass of Jupiter, and D is the distance from the planet to β Pictoris. Note that this time is similar to the duration of the phenomenon around the day 4918. Moreover, if we assume $R_{\beta Pic} = 1.2 R_{\odot}$ (Paresce 1991), an occultation by a planet crossing a diameter of β Pictoris will last a time t_{\star} , where $t_{\star} \leq 1.1(D/5\mathrm{AU})^{1/2}$ days, and will decrease the luminosity of the star by $\delta V = 8 \cdot 10^{-3} (R_p/R_J)^2$. The duration of the JD 4918 phenomenon constrains D to be greater than 0.08 AU. No upper limit can be given. For a planet with a radius 1.1 times the radius of Jupiter, we find $\delta V = 0$ ^m.01, and $\delta V = 0$ ^m.02 with a planet 1.6 times bigger than Jupiter. Thus, the measurements of JD 4918 could be explained by an occultation of the star by a planet or a group of planets (planetesimals?) which cover a little more than an area similar to the surface of Jupiter.

6. Conclusion

From the analysis of β Pictoris photometry measurements collected by the Geneva Observatory from 1975 to 1992, we have shown evidence of variations of the apparent magnitude of the star, on long as well as on short time scales.

On long time scales, we proved that the brightness of β Pictoris decreased by 0°:011 \pm 0°:004 over one thousand days. Unfortunately, the quality of the IUE measurements is too low to compensate for the lack of Geneva Observatory measurements between 1983 and 1988. However, when we consider all the measurements, the chance that there is no variation at all can be estimated to be less than 10^{-4} . This result is strongly confirmed by the comparison with the other stars on which the same tests were performed and which showed no long term variations at all.

On short time scales, peculiar variations are observed during about 30 days. These variations are regular, symmetrical and centered on a very particular day (JD 4918) on which variations may be reach $0^{m}.04$.

Except for the variations around JD 7780, they do not show color effects. The variations have the same amplitude in all wavelengths from 3464 Å to 5807 Å (U to G filters), indicating that probably large particles are responsible for these variations.

We are aware that the explanations proposed here are somewhat bold, all the more so as we do not have a lot of information. For the results presented here, it is not possible a priori to exclude a stellar origin for the observed photometric variations, rather than the proposal of the variations arising from local density variations of the disk. However, it is also difficult to show this. Thus, we have looked at an other hypothesis based on observational and theoretical information on the β Pictoris disk. These variations, on long as well as on short time scales, could be due to the presence of inhomogeneities in the disk which could be related to the presence of planets or planetesimals. It seems to be very important to continue such observations to confirm the existence of the variations, and, with the help of other observational techniques (spectroscopy, high resolution observations) build a unified model for the fascinating environment of this star.

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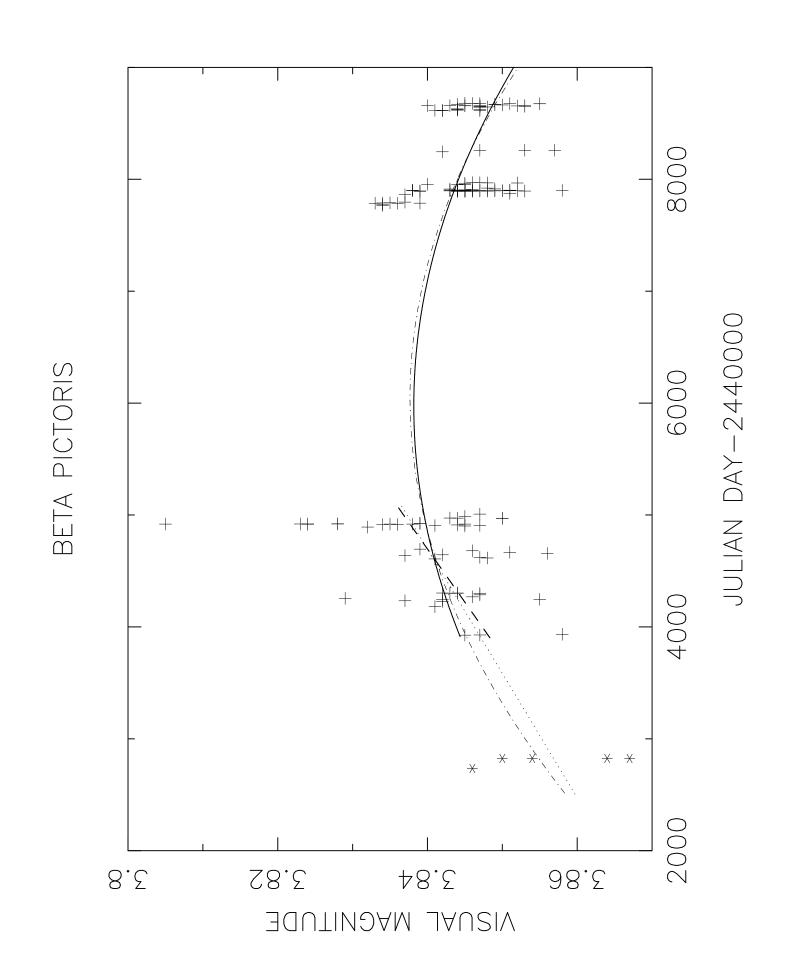
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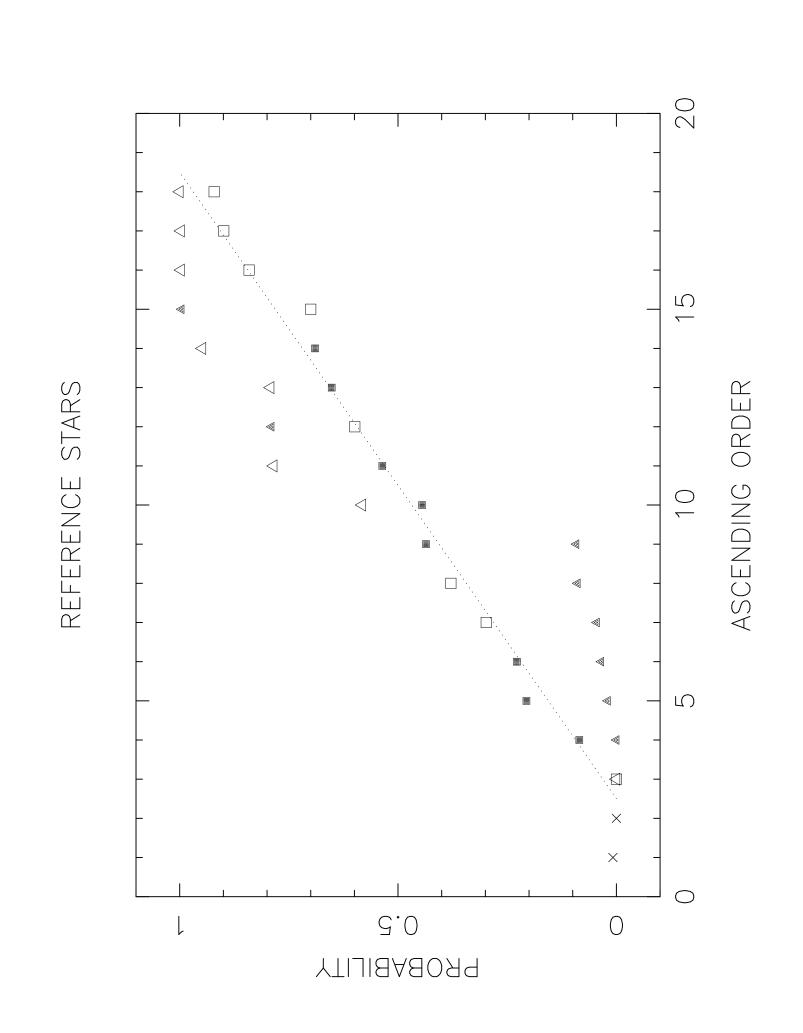
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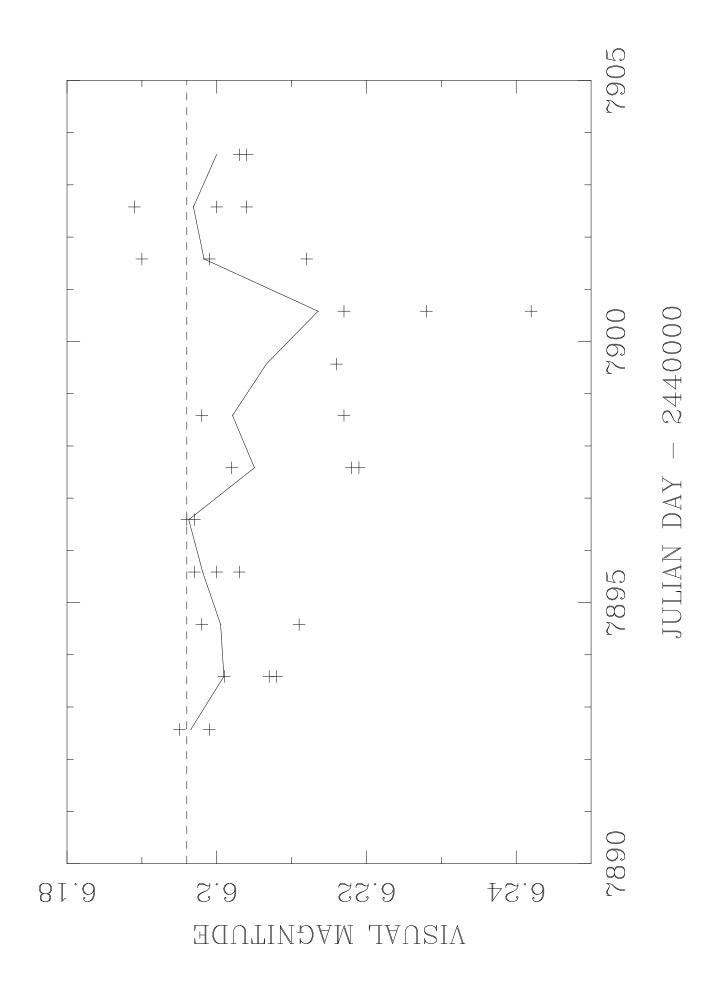
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